citrus trees that had not been protected from frost damage previously, conventions were held to discuss the frost menace, and business men in some communities banded themselves together to aid the fruit growers in lighting their heaters when necessary. The next freeze will find the southern California citrus orchards better equipped, and the citrus growers more alert, to reduce the amount of damage to trees and fruit.

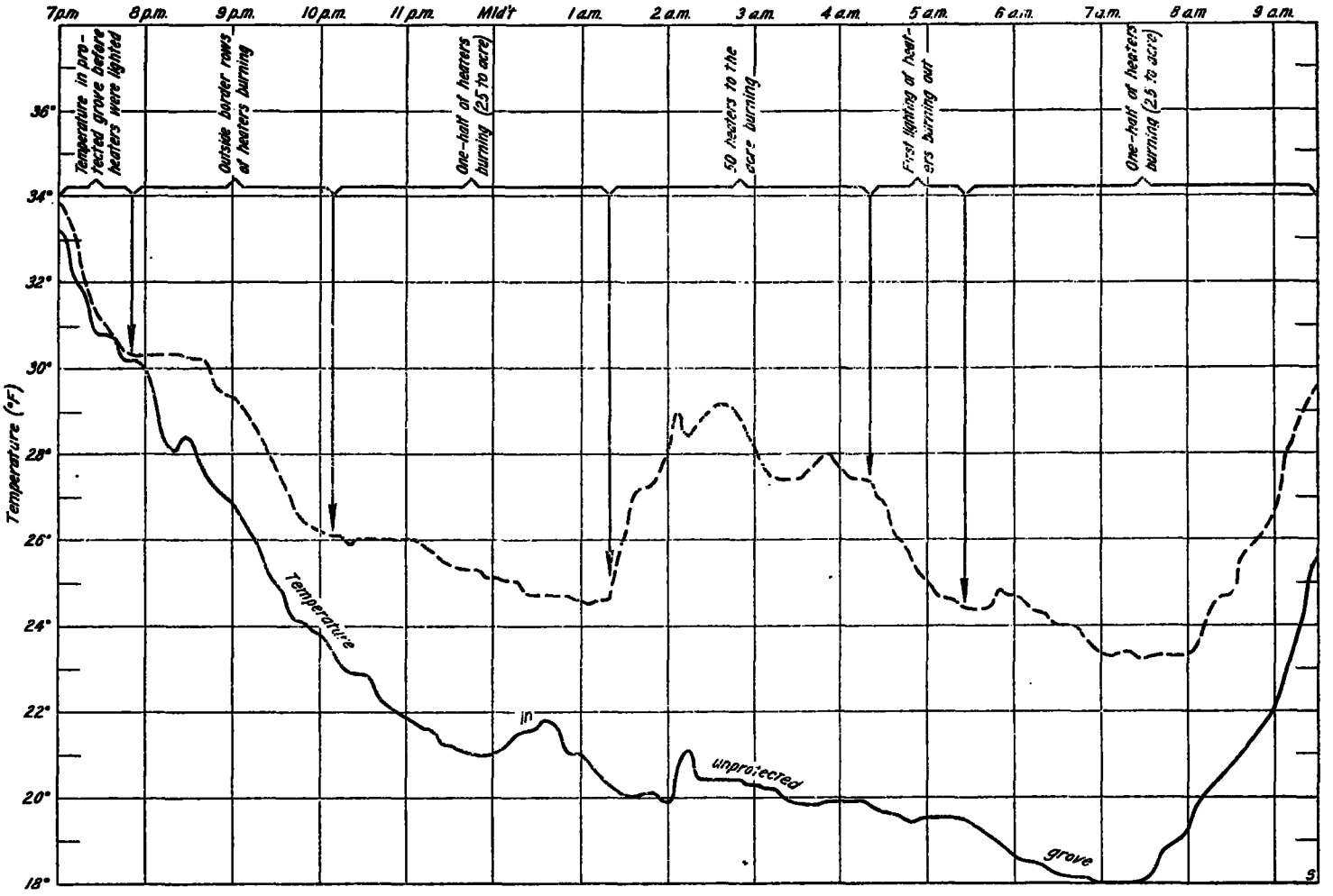

FIG. 8.—Contrast of temperatures in protected and unprotected groves.

SONORA STORMS.

By DEAN BLAKE, Meteorologist.

[Weather Bureau Office, San Diego, Calif., August 27, 1923.]

Originally "Sonora storms" applied only to those sporadic thunder showers peculiar during the summer season to the desert and mountainous regions of Baja and southern California, but at present there unquestionably is a difference of opinion among meteorologists as to their origin, movement, frequency, and general characteristics. The term as used in California has come to include any storm whose genesis is not clearly defined, or can not be definitely traced either to the normal disturbances which move in from the Pacific or to their occassional secondaries forming this side of the Rockies.

According the Archibald Campbell,[1] "Sonora storms" received their name from the old Spanish or Indian settlers of Lower California, who supposed that they began in and spread out from the State of Sonora across the Gulf of California on the mainland. He is responsible for the statement that they form during July, August, and early September only; prevail over a limited area 20 to 40 miles in width east to west, and some 600 miles in length north to south; and extend through the ranges of northern Lower California, into San Bernardino County, with their greatest development reached near the Mexican border in the Laguna and Cuyamaca Mountains. It is emphasized that they do not often occur west of the 2,000-foot elevation, and are invariably accompanied by heavy thunder and brilliant lightning. The point is also stressed that they spread eastward over the desert at times, causing excessive precipitation in places.

Willson[2] describes the "Sonora" as a deep depression extending northward during the fall months from Mexico through the interior of California, western Arizona, and southern Nevada, with the rains occurring generally in the form of thunderstorms. On the other hand, Carpenter[3] associates the "Sonora" with the sudden storms of spring on the southern California

[1] MO. WEATHER REV., October, 1906, p. 464.

[2] *Weather Forecasting in the United States*, p. 337.

[3] Climate of San Diego, Calif., pp. 10, 32; *Bulletin L*, p. 81.

coast, but makes no specific mention of any accompanying electrical phenomena. He assumes that they are overflows from Arizona disturbances, or have their inception in unchartered regions to the south.

Quoting from reprint of section 13, *Summary of the Climatological Data for the United States*, signed by A. H. Palmer:

> A peculiar feature of the precipitation is the occasional occurrence in summer of showers of the Sonora type, due to atmospheric disturbances across the international border in Mexico. These storms are wholly unrelated to the cyclonic disturbances which usually move eastward across the northern portion of the United States.

Still another type of storm has grown to be known as a "Sonora"—those tropical disturbances, usually of great energy at the outset, but gradually diminishing in intensity, which in frequently move far enough to the north along the coast of Lower California to influence the weather in extreme southern California and Arizona. The extraordinary rains in these districts on September 29 and 30, 1921, were caused by some such disturbance.[4]

From the foregoing it can be seen that, as now generally conceived, a "Sonora" is a storm presumably originating somewhere in the Southwest, and described as differing widely in its development, its area of activity, its causes, and its time of occurrence in the year. However, only one group of the many so-called "Sonoras" seems to possess characteristics sufficiently marked to warrant an appellation that presupposes a distinct and individual storm type, and that is the summer thunderstorms in the mountains and deserts of Lower and Southern California.

Of the spring rains at San Diego, mentioned by Carpenter, it may be said in passsing that these are most often caused by: (1) Secondary low-pressure areas that frequently develop at this season of the year over the southern Plateau States; (2) the southerly movement of north Pacific lows; (3) activity on the part of the semipermanent LOW area which makes its appearance over the Colorado Basin with the advent of high temperatures. It is during May that the so-called Arizona center of activity most often becomes a rain producer in southern California, and presents unusual difficulties to the forecasters of the district. San Diego records show that out of the 24 stormy periods of from one to five days during May in the past 10 years, 18 can be traced either to secondaries over Nevada and Utah, or to the sudden development of energy on the part of the Colorado Valley low area, while the remaining 6 can be traced to low-pressure areas entering the coast from the Pacific.

True "Sonora clouds" [5] are thunderclouds, and overhang the mountains and desert from the middle of June to the middle of September, reaching their greatest development and frequency in July and August. From the littoral districts in San Diego County, they appear over the ranges to the east as towering, turbulent, gigantic cloud masses which are continuously changing form and assuming the familiar anvil shape as they progress. Very often they rise to extraordinary heights, their white forms outlined sharply against the blue sky beyond, but from first to last they have practically all of the characteristics of the ordinary "thunderhead."

Their appearance is first indicated when small white wisps of cloud are noted, sometimes as early as sunrise, but usually between 9 and 11 a. m., which very quickly take on the cumulus form. Soon a line of flat-based cumuli can be discerned following the general trend of the mountain crests, that is, in a northerly-southerly direction. In less than an hour their true nature becomes apparent, and before the end of the second hour, a thunderstorm is well in the making.

It is noteworthy that throughout the entire region of their distribution convectional clouds persist for days and sometimes weeks before they attain energy sufficiently great to cause precipitation or even a "dry" electrical storm. In these instances they gather in the morning but disappear before sunset. Sometimes the rains are nocturnal but more often diurnal, prevailing for days at a time, then abruptly ceasing, leaving the sky cloudless.

Examination of available data verifies the assumption that "Sonoras" reach a maximum intensity in San Diego County, although there are other localities where they are severe. In the San Bernardino Mountains, for instance, they are of more frequent occurrence than elsewhere, but the excessive rains are lacking. The northerly limit includes the southern portion of Inyo County; the southerly, the northern third of Lower California. Downpours are more frequent on the eastern slope of the ranges than the western, and it is not unusual for the greatest 24-hour rainfall of the year to occur in the valleys and desert on that side of the mountains, although in all sections the precipitation is sporadic. Under the 2,000-foot level toward the coast, the fall is inappreciable ordinarily. No synchronous relationship has been established between these and the thunder storms in Arizona, except those which occur in the valley of the Colorado.

Certainly, the most marked feature of summer rainfall in California is the abnormal amounts reported in the south. Table 1, taken from the California section of the monthly climatological data, gives the greatest in 24 hours over the state during July and August from 1913 to 1922, inclusive.

TABLE 1.—*Greatest amounts of precipitation in 24 hours in California.*

Year.	July.		August.	
	Station and county.	Amount.	Station and county.	Amount.
		Inches.		*Inches.*
1913	Macdoel, Siskiyou	2.15	Glennville Kern	1.61
1914	Nellie, San Diego	3.75	Cuyamaca, San Diego	1.33
1915	Bagdad, San Bernardino	1.29	Julian, San Diego	1.73
1916	Crescent City, Del Norte	2.46	Cuyamaca, San Diego	1.97
1917	Elsinore, Riverside	2.00	McCloud, Siskiyou	1.13
1918	Tamarack, Alpine	1.58	Needles, San Bernardino	2.20
1919	Warner Springs, San Diego	1.26	Rose Mine, San Bernardino	1.61
1920	Fort Bragg, Mendocino	1.36	Indio, Riverside	3.61
1921	Campo, San Diego	2.90	Needles, San Bernardino	2.10
1922	Do	7.10	Warner Springs, San Diego	2.00

From the table it will be observed that in every instance except July, 1913, 1916, 1918, and 1920, and August, 1917, when the greatest catch was made in the northern part of the State, the record was established in "Sonora territory," and 53 per cent of these times in San Diego County where, as it has been pointed out, the storms are most often excessive and damaging. It is in this county that phenomenally heavy rainfalls have been recorded, the most notable of which was at Campo on August 12, 1891, when 11.50 inches was measured at the end of 80 minutes during a "cloudburst." How sporadic these showers are may be judged when we are informed that repeated cases have been known to occur with an inch or more in a restricted locality, and not a drop at a distance of a few miles.

[4] *Pilot Chart of Central American Waters*, April, 1923. (Hurd.)
[5] *Descriptive Meteorology*, Moore, p. 192.

Very often highways, railroads, and bridges are washed away, and arroyos are turned into booming streams, small farms in the river beds are inundated, and the comfort and pleasures of the many campers in the mountains are sadly interfered with. In addition, the accompanying lightning is responsinle for many forest fires; in 1922 in the Cleveland National Forest 14 out of the 39 fires reported from June to September were definitely traced to this cause. Although few actual measurements have been taken, Nelson's investigations in Lower California[6] leave no doubt but that the region of these torrential rains extends into the Sierra Juarez and San Pedro Martir Mountains, and there is ample proof of "Sonora" conditions similar in every respect to those prevailing on this side of the line.

A study of the readings for the past two years from more than 115 gages scattered throughout Imperial, San Diego, Riverside, San Bernardino, Los Angeles, and Inyo Counties was undertaken, and the following conclusions drawn concerning the storms we are considering:

(1) They are more severe and obtain oftener at the higher stations, although some places in the desert have an average comparable with that of the highest mountain exposures.

(2) Elevation for elevation, slope for slope (except in the San Gabriel Range, which has an east to west trend and lies near the ocean), both the amounts and frequency are fairly proportional throughout the district.

(3) Occasionally they occur in early September and late June, but as a rule have little energy, and result in little precipitation in these months.

(4) Unsettled weather, accompanied by local showers, often prevails over the whole area involved, from the Pacific to the Colorado River, and it is during these periods of regional cloudiness that excessive falls are most often recorded.

(5) The great Mojave and Colorado Deserts are the largest factor in their formation and development. It is in this vast arid waste and contiguous ranges to the west that the essential conditions necessary for the genesis of such storms is found. Here they become active by vigorous convection, favored by the precipitous slopes of the Sierra Nevada, with the result that thunderstorms of exceptional violence spring into being, and a glance at the map will show how closely the boundaries of the "Sonora" agree with those of the deserts, both to the north and south.

TABLE 2.—*Amount of precipitation and number of days with 0.01 inch or more at selected stations in southern California during July and August, 1921 and 1922.*

Station.	Elevation (feet).	Precipitation.				Number of days.			
		July, 1921.	August, 1921.	July, 1922.	August, 1922.	July, 1921.	August, 1921.	July, 1922.	August, 1922.
San Diego	87	T.	T.	0.01	T.	0	0	1	0
Los Angeles	293	T.	T.	T.	0.00	0	0	0	0
El Cajon	482	T.	0.07	.01	.01	0	1	1	1
San Bernardino	1,054	0.00	.00	.02	.02	0	0	2	1
Campo	2,543	5.30	.60	7.10	1.32	3	1	1	3
Warner Springs	3,165	1.53	2.03	1.53	2.35	2	5	2	3
Independence	3,957	.06	.08	.02	.33	3	1	1	4
Cuyamaca	4,677	1.81	.07	.57	1.53	3	1	1	5
Squirrel Inn	5,280	T.	T.	5.01	.00	0	0	1	0
Mount Wilson	5,704	.03	T.	T.	T.	1	0	0	0
Decker's ranch	5,850	.52	1.07	.13	.73	4	5	4	9
Rose mine	6,867	1.43	2.50	2.67	.61	2	6	5	4
Raywood Flat	7,200	1.83	.58	.48	.48	6	3	4	5
Indio	−20	T.	.72	.07	T.	0	2	1	0
Calexico	0	.06	2.84	.78	T.	1	2	1	0
Needles	477	.09	3.79	.01	1.47	2	6	1	3

[6] E. W. Nelson: *Memoirs of the National Academy of Science*, Vol. XVI, first memoir.

Before this paper was begun, it was believed that the rains in some way resulted from disturbances originating in Mexico, probably in the Tropics, but until more tangible evidence is obtained it is impracticable to assume any such hypothesis. They are limited to a well-defined and comparatively small area, and in my opinion the contributing factors must be within or in close proximity to this area. The position of the State of Sonora, lying as it does directly south of Arizona, with its contour of ground embracing desert and mountains similar to that State, and with a climate also corresponding closely in the main, disposes of this as the generating field of local storms 500 to 800 miles to the northwest. Another point worthy of stress is that "Sonoras" occur simultaneously with varying intensity over the whole region of their prevalency; have little if any horizontal movement, and run the course from their inception to termination within a radius of a few miles. Granting this as true, it is hard to give credence to any theory that presupposes a northward extension of the tropical system of summer rainfall.

In Lower California the configuration of the country, and the climate in the district north of latitude 29° is practically the same as that just north of the boundary. A diminution of winter precipitation and a gradual increase in temperature can be expected the farther south we go. Between latitude 30° and latitude 27° lies what is known as the Viscaino Desert region, and it is stated that three years have been known to pass without so much as a drop of rain in the lowlands. Below latitude 27° the summer tropical rains obtain. It is unfortunate that paucity of data prevents a detailed survey of the climatic conditions in the peninsula, but those most familiar with this section believe that there can be no connection between the tropical rains of the lower division and the occasional thundershowers of the north.

It might be of interest as bearing out these opinions to quote here from Nelson's exhaustive memoirs cited before. He says in part:

> The first of these [rainy seasons] is part of the tropical summer rainy season which regularly occurs on the west coast of Mexico as far north as northern Sinaloa, the border of which extends across the gulf to Lower California and is specially marked in the southern part of the cape district.

Again:

> The summer rainy season of Lower California * * * begins somewhat later than on the opposite Mexican mainland coast and ends earlier, usually lasting from July to October or November, September being the wettest month.

From 1913 to 1922 there have been 10 outstanding days in July and August when "Sonora storms" were particularly active, viz, July 30, 1914; July 13, 1916; July 27, 1917; July 15, 1919; July 20, 1921; July 18, 1922; July 31, 1922; August 26, 1915; August 24, 1916; and August 23, 1921. The morning weather maps of these dates had many features in common, and the positions of the areas of low and high pressure were in each case relatively the same. In fact, there was such a similarity that a type map was worked out from the barometric and thermometric means of the 10 observations for available stations west of the Rockies. Figure 1 is the result, and to show how closely it corresponds with that of a single day, the map of July 18, 1922 (a date when thunderstorms were general in the mountains of southern California and excessive amounts were reported at several stations), is also exhibited.

It has been found that, while large "thunderheads" might obtain in the district for days at a time, and even scattered showers sometimes fall, heavy and general

rains occurred only under a certain barometric distribution. The semipermanent area of low pressure invariably was charted in the Colorado Valley region, usually with an elongated extension of the isobars northward into the great central valleys of California. Another low area prevailed, as a rule, in British Columbia or Alberta, moving in a southeasterly direction. Between these lay a field of nearly uniform pressure, flanked on either side by a high area, the one impinging on the north Pacific coast, the other overlying the northern Rocky Mountain region and extending southward into New Mexico and western Texas, with the isobars trending northward and southward. Rains, other than purely local showers, in every case under consideration, occurred with a map of these general characteristics.

That the southwestern "thermal" low area is the breeding place of cyclones which detach themselves and move in an easterly direction is generally accepted, but some vital and as yet unsuspected change apparently takes

the genesis of thunderstorms is supplied in the damp air from this source. An examination of the records disclosed light, variable winds over the region on these days with all other essentials for strong vertical convection, including an adiabatic temperature gradient in evidence. Even as far west as the coast, pilot-balloon observations (also verified by cirro-cumulus and alto-cumulus movements) show an abnormal prevailing drift from the eastern quadrant above the 2,000-meter level, but below that from the west. Owing to the great number of days with low clouds over the Army and Navy fields where the balloons are released, the results are not highly satisfactory, but it is fairly well established that the "boiling over," as it were, is most pronounced on those days when cumulus and cumulo-nimbus tower above the mountains. After careful observation the writer has yet to observe a single instance of severe "Sonora" conditions when the upper cloud movement was other than from an easterly direction.

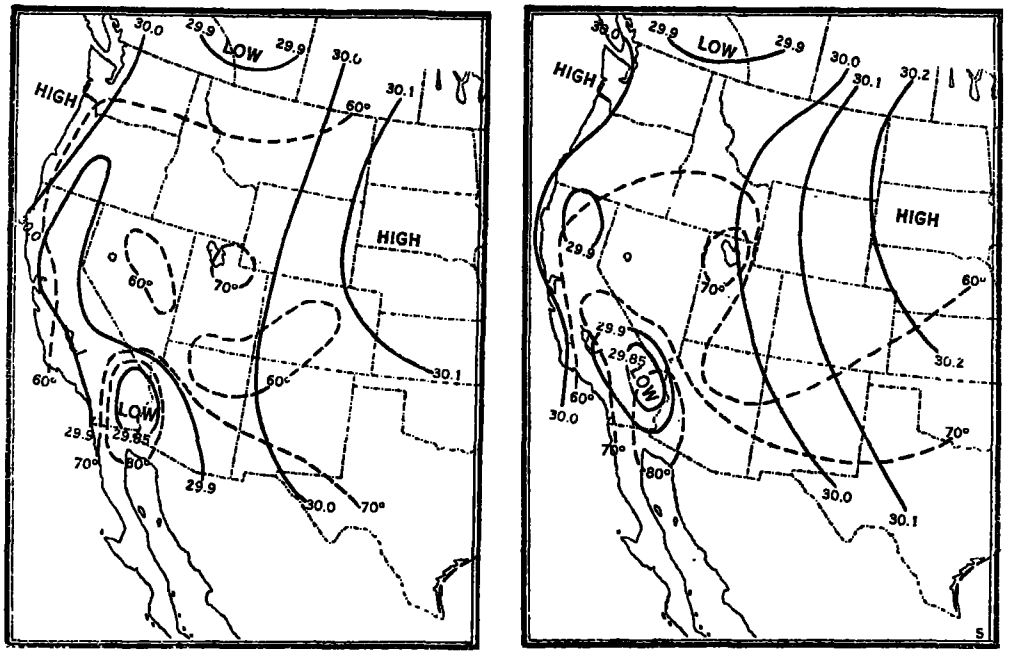

FIG. 1.—Left: Type map for occurrence of Sonora storms. Right: Map for a single day, July 18, 1922, showing agreement between the two.

place in the mechanism of the parent LOW before the separation. A definite but obscure relationship seems to exist between this breaking away and widespread "Sonora storms," for within three to five days after uncommon activity is displayed the pressure begins to fall at stations east of the Colorado River, and there is a spreading out of the low area in that direction, which either becomes a separate, well-defined depression or dissipates after a short life. Further, it is almost invariably the case that when this movement begins, a diminution in the force and extent of the "Sonora" takes place, and a fall in temperature in the mountains may be expected. What the connection is between the eastward passage of the one and the prevalency of the other is to be ascertained only after careful study and correlation is made of all available homogeneous phenomena.

To be sure, a pressure distribution such as described would be most favorable for an indraft of moist air into the Colorado Desert region from the Gulf of California to the south, and a marked relation between the "Sonora cloud" and humid weather at desert stations has been suspected. With the prevailing winds from May to October from the south, one of the essential factors in

It is not difficult to believe that over the crests it frequently would happen that much colder air from the Pacific would overrun the warm air spreading out from the east and result in what has been termed a "border storm."[7] As a point in evidence, it is in the valleys with little or no obstruction toward the desert that the excessive rains are most frequent. Northward the topography changes materially, and the ranges and arid wastes are no longer in juxtaposition. If they were, northern and central California would probably experience much the same type of summer thundershowers as in the Sierra Nevada.

In conclusion, Beals[8] has stated that this center of action has not been given the attention or thought it should have received. He has shown that some of the summer rains of the North Pacific States are produced by eddies from the superheated valleys of California. The writer, too, feels that "Sonora storms" can also be traced to the same field of activity, of which but little is known at present, and of which much fruitful investigation can be undertaken.

[7] *Humphreys: Physics of the Air*, p. 323.
[8] MO. WEATHER REV., July, 1922.